Environmental adaptation of buildings through morphological differentiation

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Abstract

Morphology and form are most common traits to be transferred from natural systems into architecture. However, such traits seldom retain any function of the imitated systems from nature, and therefore hardly represent a successful biomimetic design. The environment has a significant influence on the evolution of the specific form, arrangement, and composition of natural systems, where morphological differentiation is often sought. Many organisms employ morphological and behavioural means to complement physiological strategies for environmental adaptation. They follow special morphological rules to generate interfaces rather than shields, allowing optimal flow of matter. The more extreme the environment is the more organized and distinct in form the pelage (i.e. fur, hair, wool) becomes. In this paper, we propose to exploit morphological strategies from nature to building envelope design with the aim to facilitate adaptation to different environmental conditions while employing materials and other resources efficiently.

Keywords: biomimetics; environment; adaptation; building envelopes; architecture; morphology.

1. Introduction

With the increasing environmental awareness and the need to reduce energy demands, developing more sustainable and resilient solutions for buildings is essential. Resilience is typically associated with the capacity of an element to recover from a change, and/or respond appropriately to variant conditions. In nature, resilience is achieved by applying strategies of adaptation – the process by which an organism becomes better suited to its environment, which is fundamental for efficiency and survival over the short and long terms [1]. In some organisms, the adaptive process is accomplished through their skin functioning as an environmental filter, e.g. fur, whereas in others it is achieved through their built structures, e.g. mounds. Many organisms employ morphological and behavioural means to complement physiological strategies for environmental adaptation.

Biomimetics, the realm that seeks solutions by emulating strategies and principles found in nature, is a rapidly growing discipline in engineering and an emerging field in architecture [2]. It ranges from fundamental research to practical applications, providing ample contributions of innovative solutions to improve the quality of life [3]. Several benefits have been identified for applying biomimetics to solving building problems, such as enhancing creativity and innovation [4-6]; optimising resource use (i.e., materials and energy) in buildings [7]; lowering pollution, benefiting health, and mitigating urban heat island effects; and providing a foundation for environmentally responsive developments [8, 9]. Nevertheless, biomimetics in architecture is still an emerging field with few successful applications.

Morphology and form are most common traits to be transferred from natural systems into architecture [10]. However, such traits seldom retain any function of the imitated systems from nature, and therefore hardly represent a successful biomimetic design. In architecture, some explorations have been carried out to examine ways in which biomimetics is enhanced. For example, investigations of terminologies from life sciences that could have similar use in buildings [11]; analysing ecosystem interactions for higher sustainability and optimised resource use in the built environment [7, 12]; exploring ideas from nature for
inspiration [13]; learning from termite mounds for ventilation and thermoregulation [14, 15]; and identifying strategies of animal skins for per-formative constructions [16]. Although these explorations reveal some unique aspects from nature to inform architecture, biomimetics as an effective design tool is still a challenge. The main challenges remain: (i) the broad range of possibilities, (ii) the lack of systematic selection methods, and (iii) the abstraction and transformation of relevant principles into building solutions [17].

It is not surprising that traditional villages have compact configurations, such as in Mediterranean regions, where a cluster of houses form a continuous structure with reduced external surface-area and create comfortable microclimates in their courtyards, thus reduce a great amount of heat stress taking into account other climatic and cultural aspects. There are clear benefits from applying these strategies at the building scale, such as savings in energy and controlled heat transfer to the surrounding environment.

Natural systems follow special morphological rules to generate interfaces rather than shields, allowing optimal flow of matter. The more extreme the environment is the more organized and distinct in form the pelage (i.e. fur, hair, wool) becomes [18]. In this paper, we propose to consider the building envelope as a medium that utilizes environmental changes for adaptation. Implementing morphological solutions from nature that promote environmental adaptation can enhance the performance of building envelopes, increase occupant comfort, and potentially reduce energy demands.

2. Adaptive solutions for buildings

Environmental conditions are constantly changing and creating new challenges for building envelopes to accommodate. Occupant’s activities as well as environmental factors, such as air movement, humidity, temperature, solar radiation, air quality, noises, affect comfort inside buildings [19, 20]. Considering the building envelope as a barrier limits design solutions that utilize environmental changes. Implementing adaptive solutions that reflect environmental context can enhance the performance of building envelopes, increase occupant comfort, and potentially reduce energy demands.

Proposals for adaptive building envelopes have been emerging since the last century; some are theoretical, yet potentially applicable. A pioneering theoretical example from the 1980’s is the “polyvalent wall” [21]; it consists of thin layers that are capable to absorb, reflect, filter, and transfer energies from the environment. Nowadays, emerging technologies together with advanced manufacturing techniques have a great potential to realize more complicated concepts [22]. These technologies, in particular information technology, enable buildings to self-adjust and respond to varying environmental conditions [22]. Mechanical services attachment and integration of advanced materials are distinguished as current means for adaptation.

Some advances in building envelope design have aesthetic and functional roles, such as the Kunsthaus Graz by architects Cook and Fournier, where its free form envelope stands out of the surrounding traditional buildings, and the outer media skin illuminates as a response to exhibited art projects [23]; whereas a functional example is the Council House 2 Building in Melbourne by architect Mick Pearce, receiving a top green star rating, where the envelope consists of several systems that manage ventilation, water, lighting, and cooling, to enhance the sustainability and efficiency of the building [24]. Furthermore, advances in recent years represent a more adaptive trend in building envelope design, where responsive and kinetic principles are more prevalent [25-27]. For example, the Bio-Intelligent Quotient (BIQ) building, by Splitterwerk and Arup, consists of algae filled panels (photobioreactors) that capture heat and generate electricity [28]; and the One Ocean Thematic Pavilion, by SOMA Architecture, consists of a kinetic facade of deformable lamellas that control day-lighting [29]. Despite the existing array of advanced building designs, the majority of the building stock is static. In this paper, we propose to exploit morphological strategies from nature to building envelope design with the aim to facilitate adaptation to different environmental conditions while employing materials and other resources efficiently.

3. Morphological differentiation in nature

The environment has a significant influence on the evolution of the specific form, arrangement, and composition of natural systems, where morphological differentiation is often sought [30]. Most organisms use morphological characteristics to supplement physiological and behavioural strategies for adaptation [1, 31].
Morphological adaptation is a structural or geometrical feature that enhances the adjustment of an organism to a particular environment and enables better functionality for survival, such as size, form, and pattern [32]. It promotes thermoregulation [18, 33], water management [34], ventilation [8], and/or light management [35].

One of the fundamental characteristics of living organisms, cell, or group is their ability to maintain the internal environment within tolerable limits despite the changes in the surrounding environment [36]. Beyond generating heat metabolically, heat is transferred between animals and their environment by conduction, convection, radiation, and evaporation. In some organisms, the process is achieved through the skin functioning as a thermal medium, whereas in others, it is achieved through their built structures. Different mechanisms and strategies are adapted for different climates and for different species. For example, birds use multiple strategies for retaining heat; chickadees decrease conductance in the cold by raising their feathers and withdraw head and feet into the feathers (behavioural) [36]. They trap an insulating layer of air close to the body and in doing so reduce heat losses (morphological). They also allow the peripheral tissues temperature to drop while maintaining the core temperature (physiological). These results in a decreased peripheral circulation, increased insulation thickness, and enlarged volume, which contribute to maintaining the core temperature in a very narrow range.

Many organisms exploit morphological means to supplement physiological and behavioural strategies for water management, often functioning simultaneously with other challenges like thermoregulation. Several morphologies are distinguished to promote water management via: condensation, transportation, evaporation, diffusion, and radiation reflection. These morphologies can influence surface functionality, among others, by decreasing or increasing contact angle for hydrophilicity or hydrophobicity (respectively), creating thin boundary layers for better water attraction, providing paths to direct water, or/and moving water around. The special form of stem, the small and thin leaves, and the extensive root system, are examples for morphological adaptations among desert plants. Such stems allow water storage and self-shading situations, small leaves reduce water loss, and extensive root systems enhance moisture collection in plants.

One of the objectives of gas regulation, carried out by most organisms, is oxygen uptake and carbon dioxide release (or vice versa), which is required for energy matters in the process of food and materials oxidation [36]. Animals construct their structures, among other reasons, for protection against extremes of climates. Gas exchange may arise as a secondary problem from creating protective walls, adding to the complexity of the structure’s functional design [37]. As such, the structure may provide ways to maintain environmental optima (homeostasis). Velocity gradients generated across surfaces provide potential source of work, which might be employed by a burrowing animal to induce gas exchange in its long and narrow burrow [38].

Organisms perceive light for various purposes, such as gaining information from the surrounding environment for adequate response, or for energy matters [39]. Succulents, canopy, under-story, and diaheliotropic plants manage light interception by applying special distributions, orientations, and forms [35]. These morphological means are sometimes enhanced by the plasticity of plant’s architecture responding to different light intensities [40]. The wide field of view of compound eyes in some insects and deep-sea creatures is achieved through the structural assembly of numerous tubes that direct light (reflection or refraction) to a specific focusing area, which exhibit a compact vision system with efficient energy consumption [41]. Some colours in nature arise due to special surface microstructures, where reflection, diffraction, and scattering of wave ranges are manipulated. These microstructures can, among others, enhance radiation absorption [42], and provide a selective vapour responsive medium [43]. Plants in particular need to adapt to different light intensities for optimal photosynthesis rates. Plants’ planar area, angle of incidence, and distribution play significant roles in influencing the exposure to sun radiation [44].

4. Morphological means for building adaptation

Morphology plays a significant role in the way natural systems adapt to their environments, providing among others a functional interface to regulate heat, air, water, or/and light. It can be considered as a base for biomimetic applications for the environmental adaptation of buildings [32]. The multi-functional capabilities of systems are often enhanced by morphologies that allow several physical processes to perform simultaneously, such as some microstructures that enhance light scattering and water condensation. The following examples demonstrate certain morphological features and their potential applications for the environmental adaptation of buildings:
• The presence of wrinkles and grooves on cladding surfaces could promote cooling by holding moisture for potential evaporation and creating self-shaded areas for reduced heat loads.
• Hexagonal microstructures on skin enhance condensation for water harvesting. The hexagonal arrangement of elements such as photovoltaic cells could enhance light perception and improve energy generation.
• Spikes, knobs, and trichomes enhance condensation capabilities of surfaces in arid regions, by creating a thin boundary layer that improves water collection structures from fog.
• Semi-tubular capillary systems on surfaces of structures could improve water transportation and distribution over large areas.
• Fractal arrangement of flow systems in buildings improves energy efficiency. The presence of fractal elements at the nano-scale increases reflectivity and enhances light shielding of surfaces.
• The presence of micro lamellae on surfaces and their thicknesses variation significantly improve light absorption for potential light control and enhanced energy generation.
• Porous surfaces allow direct diffusion for de/humidification, and the potential to promote thermoregulation.
• Variable elevations on surfaces can generate velocity gradients on the surface resulting in pressure gradients for enhanced ventilation through building skins.

In terms of production, complex morphologies can be produced by emerging 3D printing technologies that enable the realization of various shapes, integrations, and material gradients. Further study on relevant scaling, material properties, and suitable production methods is essential to enhance morphological applications in biomimetic design.

5. Conclusions
Environmental conditions are constantly changing and creating new challenges for buildings to accommodate. In nature, the skin has a significant role for adaptation, where organisms inhabiting different regions have adapted distinct surface morphologies for heat, air, water, and light management, that can be applied to buildings for improved environmental performance. The morphologies are not complex in their nature, rather have distinct forms, scales, and compositions. Thus, manufacturing new systems of similar functions is possible through adapting comparable physical rules.

In practice, building envelopes are exposed to multiple environmental factors that require managing air, heat, water, and light (and probably other aspects), simultaneously. Moreover, the environmental aspects are often highly interrelated, where the regulation of one might be dependent on the regulation of the others. In this regard, morphology can be considered as a key design element towards developing multifunctional solutions that allow several physical processes to perform simultaneously. Distinguishing the adaptive role of morphology in their environmental context and during changing conditions is a significant step towards the development of new building solutions that enhance adaptation. Implementing morphological solutions from nature that promote environmental adaptation can enhance the performance of building envelopes, increase occupant comfort, and potentially reduce energy demands. Future work will focus on quantitative analyses of skins and their potential application at the building scale.

6. References
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